AN ORIENTATIONAL RESPONSE TO WEAK GAMMA RADIATION[1]

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It is now well-established that widely different kinds of animals, when induced to move in any given compass direction on a horizontal plane in a presumed constant field, will tend to deviate, clockwise or counterclockwise, from this orientation. Variations in the direction and degree of this turning tendency appear to display all the major natural geophysical periods. The variations include also aperiodic ones of an unpredictable character. Furthermore, these tendencies at any given time vary with the geographic orientation of the animals.

In searching for factors which might be concerned in these orientational variations it has been discovered that mud-snails (Brown, Brett, Bennett and Barnwell, 1960; Brown, Webb and Brett, 1960; Brown, Bennett and Webb, 1960), planarians and paramecia (Brown, 1962a), *Volvox* (Palmer, 1962; 1963), and *Artemia* and *Drosophila* (unpublished observations in our laboratory) are not only extraordinarily sensitive to very small changes in magnetostatic field but are able, in addition, to resolve the horizontal vectors of very weak fields, including the earth's.

Other studies, with very weak electrostatic fields, have proven the snails (Webb, Brown and Brett, 1959; Webb, Brown and Schroeder, 1961; Brown, Webb and Barnwell, 1962) and planarians (Brown, 1962b) to be comparably sensitive to changes in ambient electrostatic fields, changes of the order of magnitude of those to which the organisms are steadily exposed in nature. Alterations in orientation are effected by ambient field changes of the order of magnitude of fractions of a microvolt per centimeter. For this force, as with magnetism, the animals appear able to resolve the horizontal vectors.

In the course of the above-mentioned studies evidence suggested that the organisms were also exhibiting changes in orientation with time and geographic direction which could not be accounted for in terms of the magnetostatic or electrostatic responsivenesses, either separately or jointly. There were indications that the organisms were responding continuously to one or more additional geophysical factors which were pervading the controlled experimental environment.

A preliminary exploration (Brown, Webb and Johnson, 1962) provided evidence that both mud-snails and planarian worms are able to perceive small changes in gamma radiation at intensity levels of the order of magnitude of the natural background radiation and, even more remarkably, to identify the direction

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of an experimental source. Initial tests, with the same results, had been made with radium gamma, but to obtain a simpler, or more homogeneous, radiation the study was, thereafter, pursued with radioactive cesium sources. This fact is mentioned only because it suggests a lack of specificity as to the effective gamma wave-length.

Methods and Materials

The discoveries that organisms are sensitively responsive to subtle geophysical forces which pervade the controlled environments of the type in which physiological responses are usually investigated, and that variations in one of these forces can alter response of the organism to another of them (Brown, 1962b), indicated the need for a new kind of approach to their investigation. Since one is dealing with kinds of identified forces whose regulation is difficult and often impractical, and since there are probably additional effective factors which have not yet been identified, a different method has been chosen from the usual one which is that of maintaining conditions constant for all factors other than the specific experimental one varied. This alternative method involves keeping constant the experimental changes to be tested and measuring the differences between experimentals and appropriate concurrent controls repeatedly over a sufficiently long period to assure reasonable randomization of effects on the response by the uncontrolled variables. For example, a one-month period of study at a fixed time of solar day would provide reasonable randomization of a lunar daily variation which is usually present, and at the same time would largely randomize the irregular variations in response associated, through correlated geophysical fluctuations, with passage of weather fronts.

It is important that the experiments be performed at a constant restricted time of day, or time of lunar day, since it has now been established that daily variations in response may be not only quantitative, but qualitative with sign of response changing in passing from one time of day to another. Thus, indiscriminate mixing of data collected over a wide range of hours of the day may lead to an erroneous conclusion that no response occurs when, indeed, one does.

Experience has shown, in addition, that one year of data, or simple multiples of a year, are required to randomize a highly significant persistent annual variation in influence of the experimental factors upon the organisms.

In brief, the nature of the response to changes in one specific kind of pervasive geophysical factor at any particular time, expressed as difference from concurrent controls, is itself being influenced by concurrent changes in other effective and uncontrolled pervasive factors. The specific contribution of any single factor can be resolved only in terms of its effect upon being tested repeatedly over a long enough time to render the effects of the other factors equal.

The common planarian worm, *Dugesia dorotocephala*, was used in this study. The worms were collected in the field on three occasions, once during each month, June, September, and October, 1962. The worms were kept in darkened containers in the laboratory and fed beef liver twice a week.

The apparatus and three-light field, with light sources behind, to right and vertically above the starting point of the worm have been described in some detail elsewhere (Brown, 1962a).

The mean path of 15-worm samples was determined as the average angular deviation from a path directly forward at the moment the worms crossed a circular arc whose center was one inch from the starting point of the worms.

The procedure was rendered as simple as possible, and arbitrary rules clearly defined, in order that wholly inexperienced observers could be used freely after very brief instruction and initial practice. For each experimental series on any given day five worms were used. The worms were swept one by one, repeatedly, to the starting point with a very fine sable-hair brush and oriented in a direction between the 0° and −10° axes on the underlying polar-coordinate grid. Numerous data had established that in such a three-light field the mean path of the negatively phototactic worms displayed a mode near −25° with an approximation to a normal distribution about this value.

As in all previous comparable studies of orientation of these planarians in such an asymmetrical three-light field, only worm starts which terminated in the worm crossing the one-inch arc between +5° and −50° were recorded. The path of each worm was recorded to the nearest 5°. On the most favorable days when the worms were moving well, less than 5% of the starts were failures. On the worst days, when many starts led even to immediate sharp U-turns, especially for some particular compass-direction for that day, as many as 50% to 60% of the starts had to be excluded on this same arbitrary basis.

The gamma sources comprised circular pieces of filter paper, four inches in diameter, upon which had been placed 24 μc. of Cs^{137} distributed uniformly in 8 spots equidistantly spaced on the perimeter of a 3½-inch circle, and a ninth spot in the center. The paper was sandwiched between plexiglass plates. The Cs^{137} plates were generously prepared in the radiation laboratories of the Marine Biological Laboratory, Woods Hole, Massachusetts, by Dr. R. J. Grabske of the Department of Physiology, University of Kansas, and Dr. Patricia M. Failla of the Argonne National Laboratory, Lemont, Illinois. The relation between plate distance in inches at right angles to the plate center and radiation intensity expressed as a multiple of background at Woods Hole is shown in Figure 1. This relationship was determined with the aid of a Tracerlab Monitor, #SU-3D. The sources, and dummy sources without the Cs^{137}, were placed in heavy envelopes and labelled X or Y by a person other than the worm-observer employing them.

The plates were hung on the outside of the wooden orientation chambers within which the worms were observed. The plates, unless otherwise specified, were placed so that their centers lay seven inches to right or left of the starting point of the worm paths. At this distance the intensity of gamma radiation at the position of the worms was about 6 times that of the natural background.

North- and West-Directed Studies

These observations were made on 36 afternoons, between 12:30 and 3:00 o'clock C.S.T., distributed as uniformly as was practical over the two-month period (59 days) from August 8 through October 5.

At each observation period, two observers, employing identically constructed apparatus, determined the average of 15 paths of worms under each of eight conditions. The conditions comprised four samplings of worms with the apparatus and initial path of the worms directed compass north, and four samplings with worms directed west. The order of presentation of north and west was varied

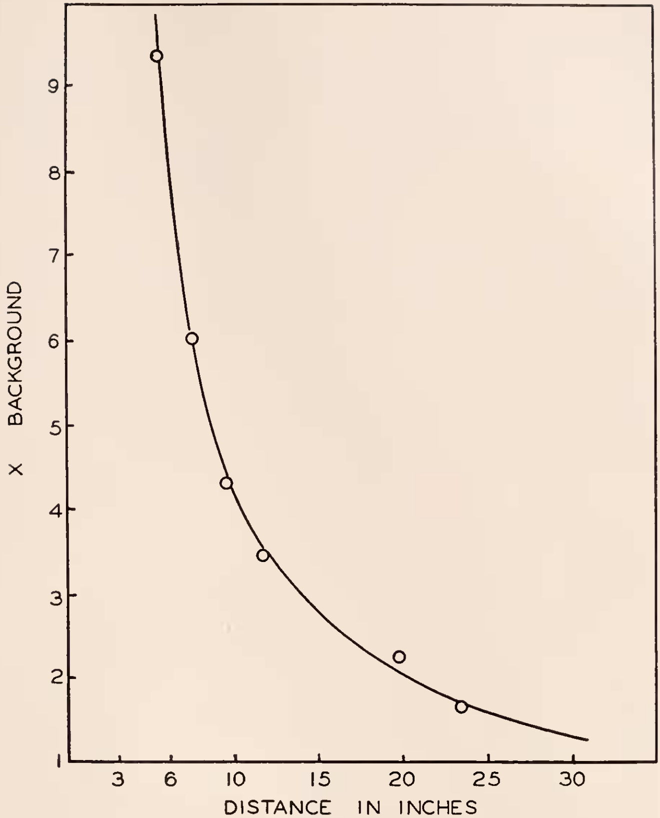

FIGURE 1. The relationship between distance from the sources used in this study and radiation intensity expressed as a multiple of the natural background radiation.

from one observation period to another. For each direction the mean path of the worms was determined under four conditions. These conditions were gamma source to right, gamma source to left, dummy source to right and dummy source to left, with the four offered in shuffled order; the observers were uninformed as to which envelope contained a source and which a dummy.

To learn whether the worms exhibited a measurable response to a Cs^{137} source, the mean path for each, $gamma_{Right}$ and $gamma_{Left}$, for each direction, was computed as the difference from the mean paths, in the same series of four, with the dummy to right and to left. It is evident that were there no response to the Cs^{137} source, the difference between the paths in the presence of the Cs^{137} source and those in the presence of the dummy controls should average zero. A significant difference from zero would indicate a responsiveness of the worms to the weak gamma sources.

Furthermore, if there was indicated by the preceding test that a response to the 6-fold increase in gamma radiation occurred, then any significant difference between the mean response when the gamma source was to the right and when it was the same distance to the left would indicate an ability of the organism to distinguish the direction of the source.

Results: The results of the two-month investigation are summarized in Figure 2 for north-directed worms and in Figure 3 for west-directed ones. Each point is the mean difference between the experimental (gamma$_R$ or gamma$_L$) and the average of the two controls (dummies) for the two experimental series of the same afternoon.

It is evident that for the worms initially directed northward in the earth's field, the gamma source on the left induced turning of the worms to the right and gamma to the right induced turning to the left. For the two average responses the values, $+1.157 \pm 0.389°$ and $-1.260 \pm 0.274°$, were obtained. Student's t in the two in-

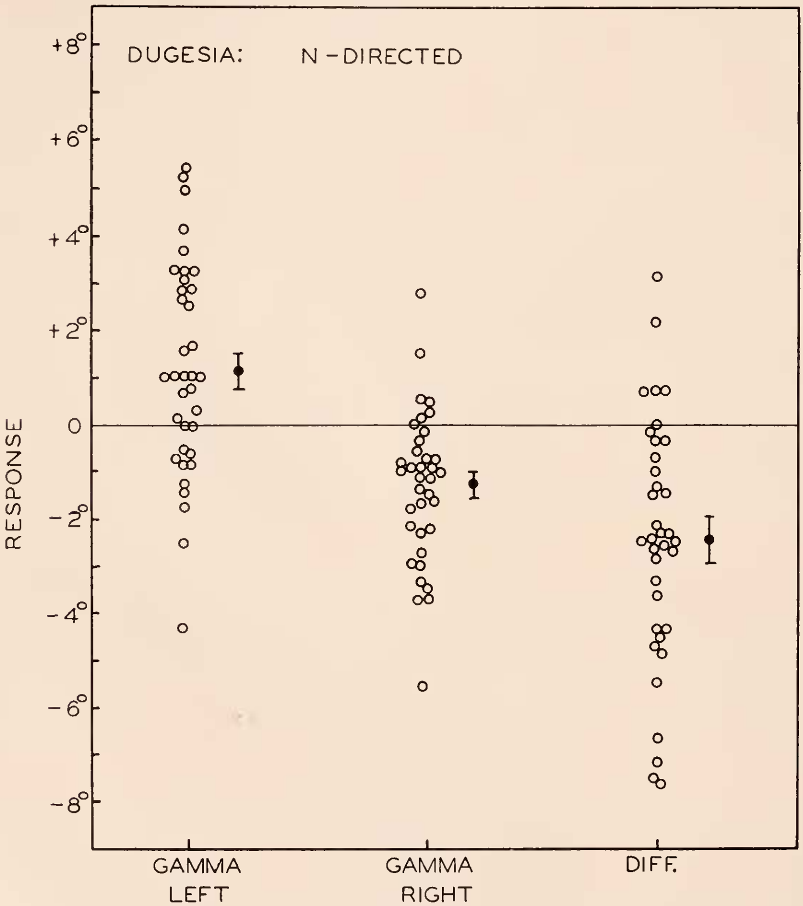

FIGURE 2. The distributions for N-directed worms of responses of 30-worm-path samples expressed as difference from concurrent controls in the earth's natural field alone. Response, expressed in degrees, is + to the right and − to the left. DIFF. is the difference between the two responses, to gamma$_R$ and gamma$_L$, for each of the the 36 experimental series taken separately.

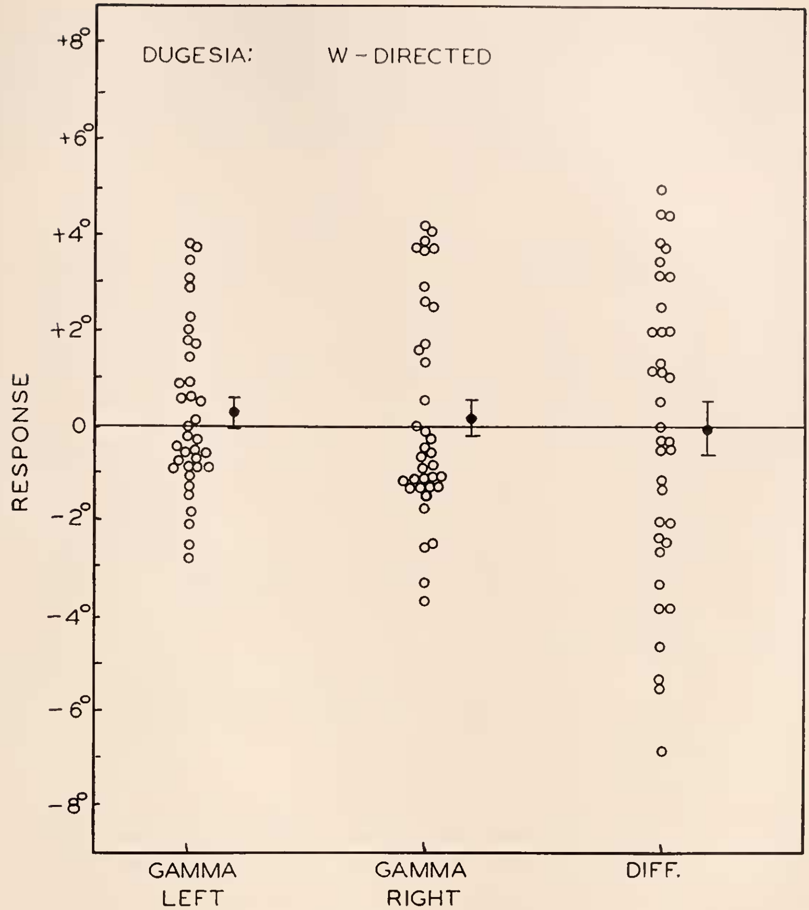

FIGURE 3. The distribution for W-directed worms of responses of 30-worm-path samples expressed as difference from concurrent controls in the earth's natural field alone (see Figure 2 legend).

stances, 3.03 and 4.69, respectively, with N in each case being 36, indicates high significance. Combining the two, the worms turned away from the gamma source, which ever side it chanced to be, with an average response of $1.208 \pm 0.235°$; $t = 5.14$, $N = 72$.

The data of each of the two observers, treated separately, indicated clearly this negative response. No reasonable doubt exists that the worms not only are able to perceive the presence of the gamma source, but to distinguish the direction of the source as well.

It is interesting, as seen in Figure 3, that when initially directed westward, the worms exhibit no similar orientational response to the gamma sources even though the experiment has, other than in compass direction, been conducted in exactly the same manner and at the same time as for the north-bound worms. Although no significant difference in mean paths between experimentals and controls in the west-bound worms is present, it is suggestive that with a probability of about 5% or less, the variance of paths with gamma to left is larger than variance with gamma to right in the north-bound worms and the corresponding difference reversed for the west-bound ones.

South- and East-Directed Studies

Even before the conclusion of the north- and west-oriented studies, other fully comparable studies were commenced involving south and east orientations. These were conducted over the period September 27 to November 2, inclusive. Responses to the gamma radiation were assayed on 26 different days distributed over the whole 36-day period. Three new observers were employed. These latter observers were completly uninformed about the nature of the previous results and, in fact, had no knowledge of the character of the problem. Sixty per cent of the observations for south and east were made by the three new observers; the remainder were made by the same observers who worked with north and west studies, still working uninformed as to the conditions obtaining at the time of their observations. Four identically constructed pieces of apparatus were used. The experiments were now performed over a wider range of afternoon hours, from 12 noon to 5 P.M., C.S.T., the greater time-span probably contributing in part to the slightly greater variability encountered.

Results: The results are illustrated in Figures 4 and 5. Each point represents the average response of 30 planarians to the gamma radiation, with 15 paths having in every case been determined by one person and the second 15 by another person. The second person was working either concurrently with the first, or following the first by a short interval.

As in the N and W studies, the results of each individual observer, in this instance now five, independently demonstrated the turning response of the worms away from the side of the gamma source when the apparatus was directed southward and the lesser, or no, response of this nature when E-directed.

Again, it was also clearly apparent that nothing related to the order in which the series was run contributed to the response. It was immaterial whether Gamma_L preceded Gamma_R in a series, or the reverse, or whether in a double series E preceded S, or the reverse. When directed southward, the worms turned significantly away from gamma on the left ($+1.403 \pm 0.458°$; $t = 3.06$, $N = 37$) and away from gamma on the right ($-1.402 \pm 0.530°$; $t = 2.65$, $N = 37$). Or expressed in another manner, the worms turned away from the gamma source, without regard to what side it was on, $1.402 \pm 0.363°$ ($t = 3.867$, $N = 74$).

On the other hand, when the worms were directed eastward, the worms did not turn significantly away from the gamma source. For Gamma_L, the mean response was $+0.854 \pm 0.455°$; $t = 1.88$, $N = 39$. For Gamma_R, the response was $-0.124 \pm 0.526°$; $t = 0.24$, $N = 39$. For response away from the source, irrespective of the side the source was placed, the response of the E-directed worms was $0.489 \pm 0.346°$; $t = 1.41$, $N = 78$.

Combined results: The principal results are summarized in Table I. Taking all data, with no selection of direction of orientation nor particular side for the gamma source, the worms, on the average, clearly turned away from the gamma source. Whether one tests probability by means of student's t, which assumes a normal distribution of responses ($t = 5.08$; $N = 296$), or resorts to a non-parametric, Chi-square test with one degree of freedom, which makes the simplest possible assumptions ($\chi^2 = 36.9$), there is no reasonable doubt that the worms not only perceive the experimental introduction of the gamma source, but recognize the

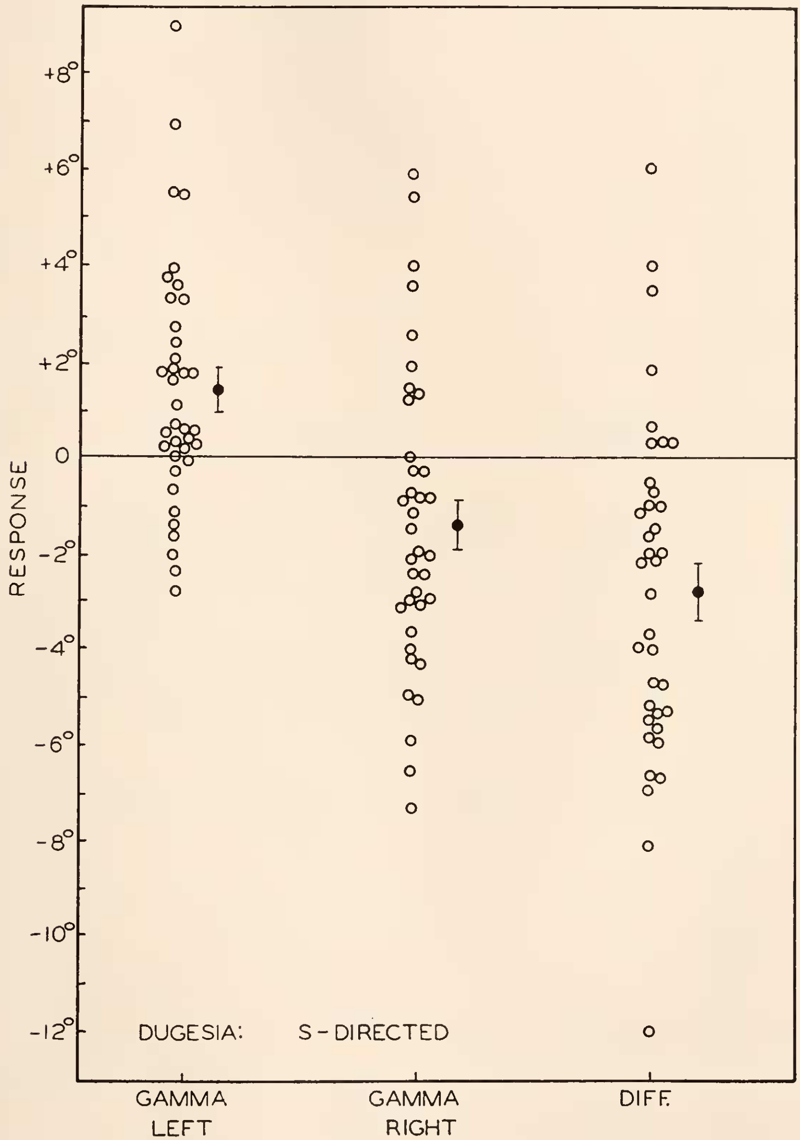

FIGURE 4. The distributions for S-directed worms of responses of 30-worm-path samples expressed as difference from concurrent controls in the earth's natural field alone (see Figure 2 legend).

side upon which it is placed. But further inspection of Table I confirms that this very highly significant response has been based almost entirely upon the avoiding response to gamma when the worms were crawling northward or southward in the earth's geographic field; only a small contribution comes from E-directed observations, and none from W-directed ones.

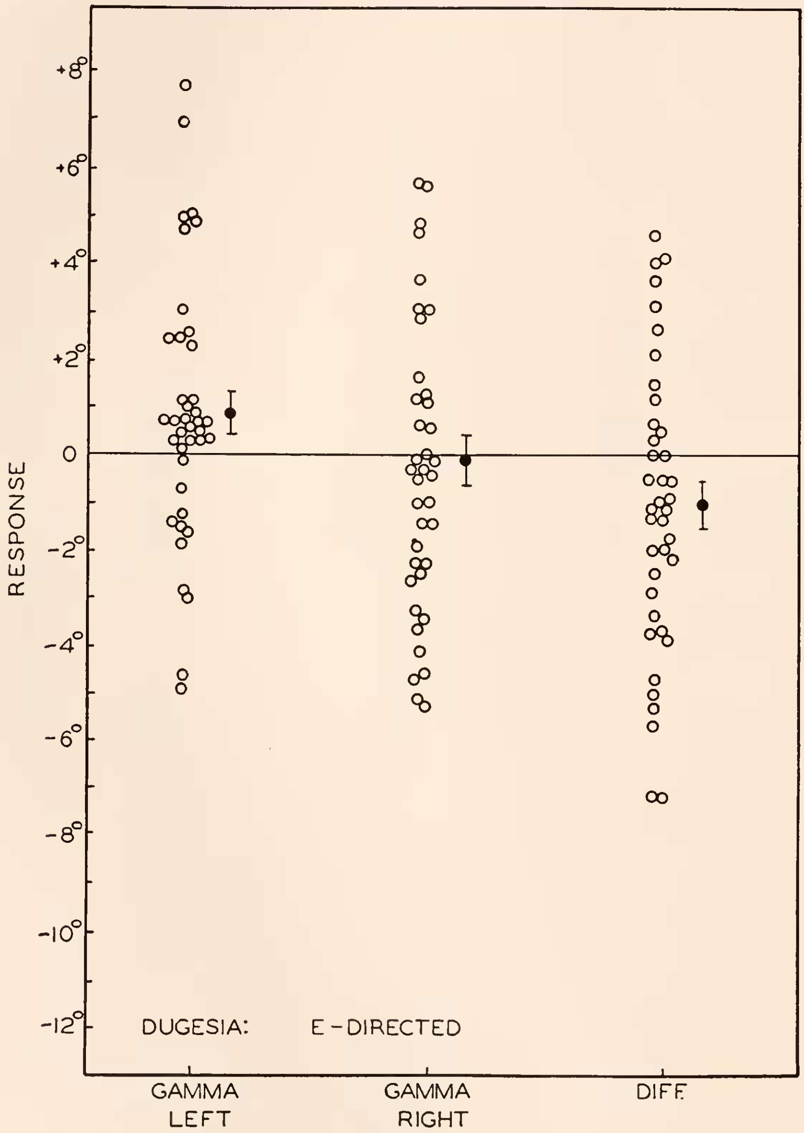

Figure 5. The distributions for E-directed worms of responses of 30-worm-path samples expressed as difference from concurrent controls in the earth's natural field alone (see Figure 2 legend).

TABLE I

Summary of gamma responses relative to geographic orientation

Direction	Response to gamma source	No. of samples of 30 paths	Number of cases away	toward	neither
N	−1.208 ± 0.2352 (t = 5.14)	72	52	16	4
			(χ^2 = 19.05)		
E	−0.489 ± 0.3455 (t = 1.47)	78	51	26	1
			(χ^2 = 8.13)		
S	−1.403 ± 0.363 (t = 3.86)	74	54	18	2
			(χ^2 = 18.01)		
W	+0.029 ± 0.238 (t = 0.12)	72	38	32	2
			(χ^2 = 0.51)		
Combined N and S	−1.307 ± 0.216 (t = 6.05)	146	106	34	6
			(χ^2 = 37.05)		
Combined E and W	−0.2402 ± 0.2125 (t = 1.13)	150	89	58	3
			(χ^2 = 6.54)		
All directions	−0.781 ± 0.1538 (t = 5.08)	296	195	92	9
			(χ^2 = 36.90)		

MONTHLY RHYTHM OF NORTH-DIRECTED WORMS

In an earlier published account (Brown, 1962a) a monthly rhythm in tendency of *Dugesia* to veer from a northward path was described to continue over about a 17-month period and to exhibit what appeared to be an annual variation in the form of the rhythm. From about September to about March there was a unimodal monthly fluctuation with maximum right-turning near full moon and left-turning near new moon. This became transformed about March or April into a semi-monthly fluctuation with maxima in right-turning near both new and full moons.

Observations on deviations in paths of north-bound worms have now been continued for about an additional year preceding, and concurrently with, the present gamma study. The results are seen in Figure 6. Confirming strikingly the earlier study, it is evident that a semi-monthly variation, with maxima in right-turning near both the times of new and full moon, occurred again during the warmer months, with the form of the fluctuation becoming converted into a unimodal monthly one in September. This latter type of monthly rhythm continued through the fall and winter, bearing the same phase relations to elongation of the moon that had obtained during each of the preceding two years except for an apparent tendency to revert to a transient, but typical, semi-monthly form of cycle in late January and through February. There was a return to a full-month cycle in March and onward past the dates of full moon and new moon in April (not included entirely in Figure 6). As with the earlier investigation of this monthly variation, the observations were made always between 8:30 and 11:00 A.M.

It is evident that the present study on responses of *Dugesia* to weak gamma radiation was being conducted during a period when this lunar rhythm was alternating between semi-monthly and monthly cycles.

A Monthly Variation in Response to Weak Gamma Radiation

In an experimental series commencing on September 27, 1962, and extending through April 13, 1963, the influence of a series of strengths of gamma radiation on worm orientation was assayed, usually on four to six mornings a week. The gamma sources in this series were presented always on the right, or east, of worms moving northward.

Each of two observers on each morning determined the path of 15 worms under four strengths of the experimental gamma field, 9, 6, 3, and 1.5 times the background. The gamma field samples of 15 paths were alternated with control runs (with dummy sources) of 15 worms in the earth's field alone. The order of

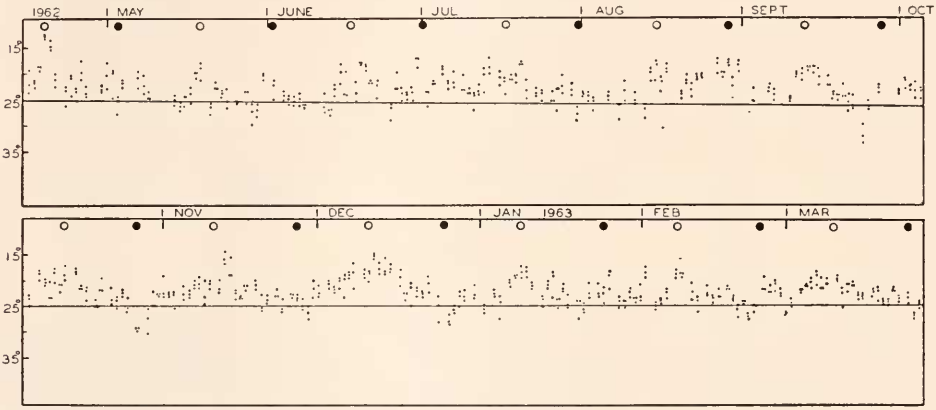

Figure 6. Variations in the character of the monthly orientation rhythm of north-bound *Dugesia* over nearly a year (see text).

presentation of the four gamma strengths and whether the controls preceded or followed each gamma run was determined for each daily series by lot. Furthermore, although each observer could note during an experimental series what gamma strength was involved in each pair of samples, the observer was always uninformed as to which of a pair was control and which was gamma. There was thus full protection against any unconscious biasing of the results by an observer.

The results which were obtained during the first 40 days are expressed as the mean difference in degree between all eight controls in the two daily series and all eight gamma fields, including the four different strengths. These results are illustrated as a function of calendar date in Figure 7A. A monthly variation is strongly suggested, with maxima in positive response occurring near the times of first quarter of the moon and the minimum occurring near third quarter. However, such a unimodal monthly fluctuation did not persist beyond this single cycle, but rather appeared to become converted abruptly to a semi-monthly one with maximum turning from the gamma source during a four-day period before both new and full moon and maximum turning toward the source during two days following these times. By December 4 three such semi-monthly cycles had clearly suggested themselves by inspection of the data. These data are depicted in Figure 7B, for the period October 20–December 4, in relation to the days of new and full moon. It is evident that during the four-day periods preceding the two moons there were 10

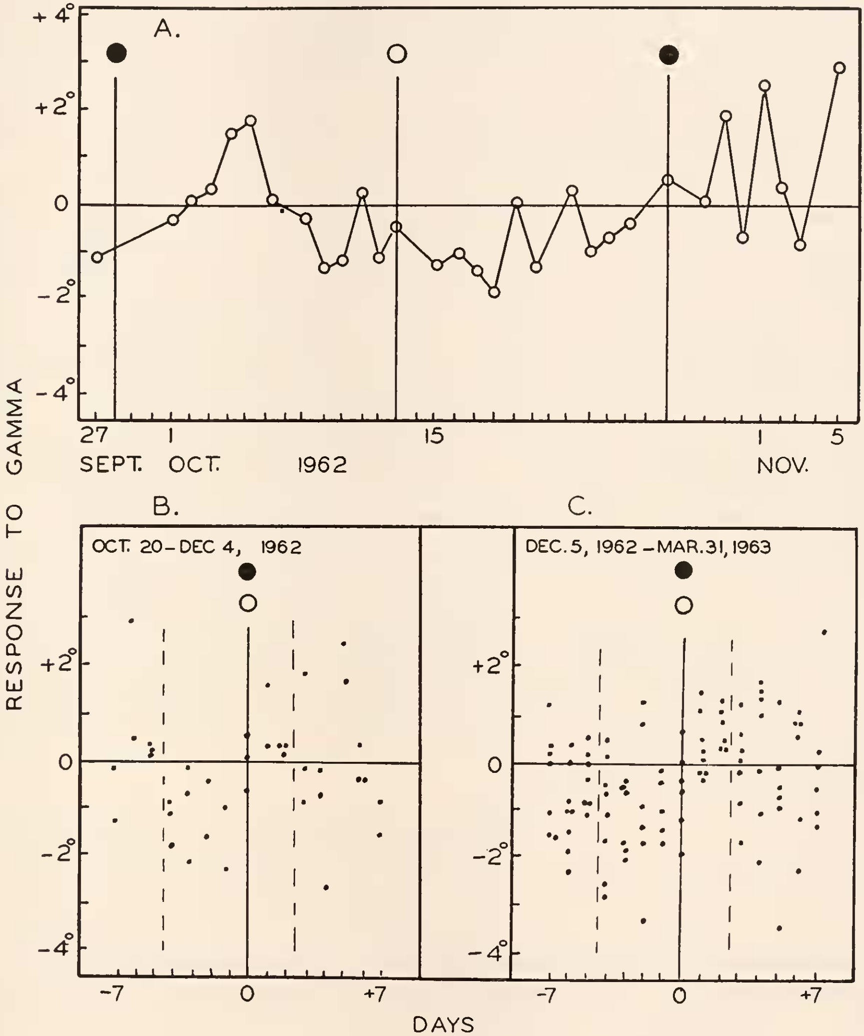

FIGURE 7. A. An apparent monthly fluctuation in response of *Dugesia* to all four strengths of gamma sources (from 1.5 × to 9 × background) presented on the right over the period from September 27 to November 5, 1962. B. A suggested semi-monthly fluctuation in response during three semi-monthly periods (October 20–December 4) with left-turning during four days before new and full moons, right-turning for two days afterwards, and high dispersion of responses for the remainder of the cycles. C. Confirmation for such a semi-monthly pattern derived from the study of an additional 8 consecutive semi-monthly cycles.

negative and no positive responses, and during the two days after these times there were 5 positive and no negative responses. During the remainder of these semi-monthly periods, the range of variation exceeded the total range of the first two periods but exhibited no consistent tendency toward either positive or negative responses.

Supporting the non-parametric estimations of probabilities, parametric consideration of these data indicated (1) the worms to be turning away from gamma sources during the four days before new and full moon with $P < 0.05$, (2) a difference between the mean for this interval and that of the two days after new and full moon with $P < 0.02$, and (3) the variance during the period from third to seventh day after new and full moon to be greater than that of either of the other two intervals with $P < 0.05$ in each case.

This hypothesis that the semi-monthly pattern had not occurred by chance was next tested over the period, December 5–March 31, which included 8 complete cycles. The results are illustrated in Figure 7C. Just as for the first three cycles shown in Figure 7B, the sign of the mean responses to the gamma fields rapidly altered from clearly negative to clearly positive in passing over the days of each new and full moon. The worms again turned during the second, and test, period statistically highly significantly to the left during the four-day period before the moons and to the right during the two-day interval afterwards. The parametrically determined significant probabilities were $P < 0.05$ for left-turning during the four days before the moons, and $P < 0.01$ for the difference between mean turning of this interval and that of the two days after the moons.

Equally apparent in both the initial three cycles and the additional confirmatory eight cycles is the exaggerated variability in response to the gamma sources during the interval from the third to seventh days after new and full moons or, in other words, as the moon's quarters are approached. The range exceeds that of both the positively and negatively responding periods combined. The variance is statistically significantly higher than for the positive period ($F = 4.33$; $P < 0.01$) but not, however, for the negative period ($F = 1.35$). It seems reasonable to postulate that this interval approaching the quarters of the moon is one in which there are continuing responses to the gamma field but that the response is sometimes positive and at other times negative.

The average form of the semi-monthly variation is illustrated in Figure 8A for all four strengths for the entire period of 13½ semi-months and in Figures 8B, C, D, and E for each of the four strengths of the gamma field taken separately. It is evident that in passing from the 1.5 × field to the 9 × one there is a progressive increase in the amount of turning away from the gamma sources during the quarterly periods preceding the new and full moons. Consequently, there is a progressive increase in the conspicuousness of the semi-monthly variation in response. This relationship between field-strength and response will now be analyzed.

Relation of Response to Gamma Field-Strength

As described in the preceding section a total of 160 double series of the four gamma strengths were obtained between September 27, 1962, and April 13, 1963. In view of the demonstrable semi-monthly variations in the sign of the response of the worms to the gamma sources, the data were reduced arbitrarily to the ten

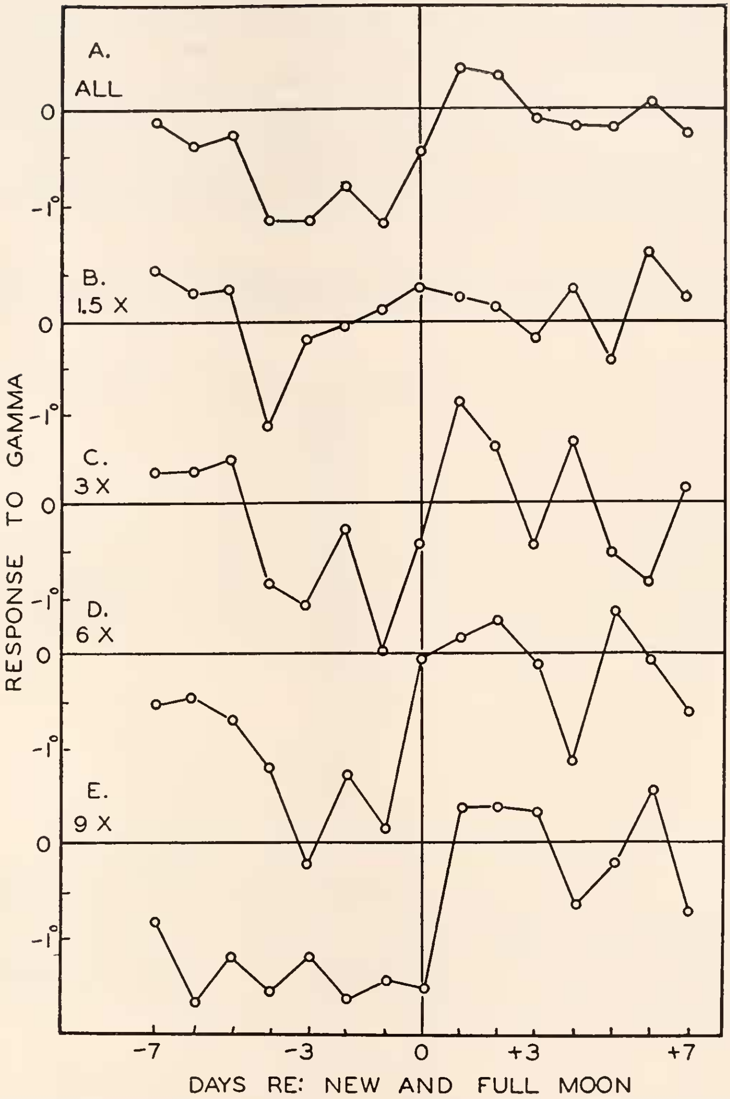

FIGURE 8. The mean apparent response to all four gamma strengths presented on the right in the morning as related to day of a natural semi-month. B, C, D and E. The same as above but for each gamma strength taken separately.

consecutive groups each containing 16 experimental double series. Since the data were obtained over about 13½ semi-monthly periods, the division of the data into ten groups assured that each group would include a reasonably sized sample of the large range of variation which was encountered. In Figure 9A are depicted the responses to the gamma sources for each of the four field-strengths expressed as the mean difference for each strength from the average of all the interpolated controls in that series. Each point, therefore, is the average difference of 480 worm-paths from 1920 control paths taken at the same times during the same experimental period. The small x's in the figure indicate the four actual arithmetical means. The solid line is the best straight line estimated by eye to include the four means and transect zero on the ordinate at 1 × on the abscissa.

It will be recalled that the gamma sources were always presented on the right. The mean overall response for all four fields is seen to be a negative one to the source. Thirty-one values indicated left-turning, 9, right-turning ($\chi^2 = 12.1$; $P < 0.001$).

It is evident from the data in Figure 9A that there was a graded mean response which was related to the field strength. The response was greatest for 9 × and least for 1.5 ×.

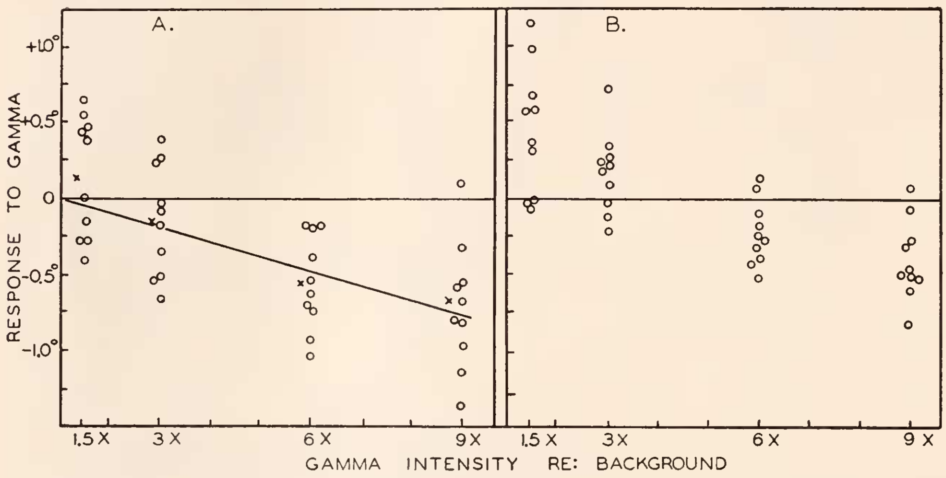

FIGURE 9. A. Difference in paths between planarians in the earth's field alone and in a field with a gamma source to the right in the morning at each of four gamma intensities expressed as multiples of background. Small x's within the figure are the means. Each point for each field strength represents the mean difference for 480 worm-paths. B. Same data as in A replotted as deviations from mean responses for the concurrently obtained four field-strengths, in order to reduce any correlated variation in the series which was a consequence of common controls, or secular trends, through the experimental period.

The method of reduction of the data, in which the response to each of the four gamma strengths in each sample series was computed as deviations from a common control, would obviously be expected to contribute a correlated variation among the responses to the four field strengths. This contribution, together with any biological alteration in responsiveness to the unilateral gamma field over the course of the seven months, was reduced by re-expressing the responses to each of the four strengths as deviations from the mean response for the four as a group in each sample period. These values are plotted in Figure 9B. That considerable variation was correlated in the data of Figure 9A is apparent from the reduction in dispersion of data for the three stronger gamma fields.

The solid linear regressional line drawn in Figure 9A appears to be about as good a fit to the data as the dispersion of the values permit. The values of Figure 9B treated as a linear correlation between angle of response and field strength yielded $r = -0.735$. The probability that this is not zero is < 0.001 ($t = 6.68$; $N = 40$).

The foregoing relationship could not be expected to obtain by chance were the worms either insensitive to the imposed weak gamma fields, or unable to distinguish the differences in strengths among these weak fields.

In considering Figure 9 it should be recalled that the response was an orientational one to gamma presented to the right or east. Although, for example, 1.5 × and 9 × involved a 50% and 900% increase, respectively, relative to total background gamma, the percentages were undoubtedly greater with respect to any east-west vector of background gamma radiation. A horizontal contribution to natural background gamma radiation would be expected to be relatively small in comparison with a vertical one.

There is a suggestion from the decentralization of the values that the response to the 1.5 × field may be sometimes negative and at other times positive. The negative cluster of data in Figure 9A was, in four out of five cases, obtained in the fall (the first five groups), and four out of five of the positive cluster of values were obtained in the winter. This suggestion, that to such weak gamma fields there may be an annual variation in sign of response, is being investigated further.

Additional suggestion that the response to the 1.5 × field includes sign reversals comes from Figure 9B. In this figure the responses of the worms to the four field strengths, treated as correlated variables, show substantially decreased ranges and variances for the three stronger fields but no comparable reduction for the 1.5 × field.

Influence of Alteration of Electrostatic Field on Gamma (6 × Background) Response

This experimental series was performed 304 times by several observers working between 1 and 5 PM during the period from November 5, 1962, to April 15, 1963. Each afternoon run consisted of assaying 15 worm-paths under each of the following 8 conditions: 152 series were run *north-directed*—Gamma$_{Right}$ (1) 2 V/cm. electrostatic field in air with + to left and (2) equipotential plates as control); and Gamma$_{Left}$ (3) electrostatic field with + to left, (4) control; and Gamma$_{Right}$ (5) electrostatic field with + to right, (6) control); and Gamma$_{Left}$ (7) electrostatic field with + to right, (8) control. The other 152 series differed only in that they were *south-directed* always. The order of Gamma$_R$ and Gamma$_L$, ES field and control, and ES$_L$ and ES$_R$, was randomly varied. The time of day was the same as that of the initial experiments of the late summer and early fall when it was found the worms would turn away from the gamma source.

In Figure 10 are shown the differences between the mean path of the worms when the gamma source was on the right and the path with gamma on the left for the worms in the control or equipotential right-angle field (= "Diff" in Figure 2). Each datum is the average of the two groups of 15 paths in each gamma orientation during each single afternoon series.

It is evident from Figure 10A that, oriented *southward,* the worms turn further to the left when gamma is on the right than when it is on the left. The mean difference was $-1.048 \pm 0.2355°$ ($t = 4.45$, $N = 152$). On the other hand, when the worms were oriented *northward* (Fig. 10B), the worms did not, on the average, turn significantly away from the gamma plate (mean $= -0.508 \pm 0.276$; $t = 1.48$, $N = 152$).

That the northbound worms were always responding to the gamma source, but sometimes positively and at other times negatively, is suggested by two observations: (a) the shoulders of the distribution are broader, and (b) the variance for the

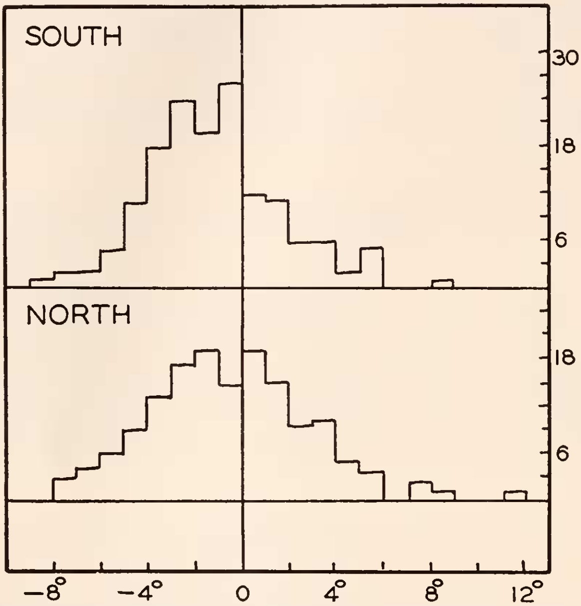

FIGURE 10. Frequency distributions of differences in path of southbound and northbound *Dugesia,* moving between large equipotential plates in the afternoon, when a gamma plate was to the left and when it was to the right (6 × background). Negative values indicate turning away from side of gamma source, positive values, toward source.

N-bound responses is significantly higher than the variance of the S-bound responses ($F = 1.37$; $N_1 = 152$, $N_2 = 152$; $P < 0.01$).

DISCUSSION

The results of this investigation add one additional environmental factor to the gradually increasing list of ones to which the living system is responsive. This one, like magnetism and electrostatics, pervades the usually controlled conditions of the physiological laboratory. Gamma radiation is highly penetrating. Furthermore, gamma radiation is a vector force, possessing direction as well as intensity. The sources of the gamma radiation contributing to the natural background are many and diverse and the radiation would be expected to possess at any given moment a specific three-dimensional pattern, just as does the natural environmental visible-light field.

This study has left no reasonable doubt that the planarians perceive not only the experimental change in gamma intensity, but distinguish field strengths, and the direction of the source, as well. Therefore, it would appear reasonable to presume that a living system is able to resolve and show responses to the detailed characteristics of the three-dimensional natural gamma field and to any variations in this field that may occur in nature. Differences in vector pattern with different geographical loci might be recognizable, as might also any alterations in the pattern related to phase angles in such natural geophysical cycles as the solar day, lunar day, month and year. In brief, this demonstrated remarkable sensitivity of the living organism to gamma radiation provides another potential source of information available to the organism to contribute toward refinements in its adjustment to the specific planet upon which it lives.

The mechanism by which the organism is able to respond to these very weak gamma fields is not immediately evident. Obviously, receptive mechanisms would gain no particular advantage by a superficial location on the body. These very low experimental intensities, of course, increase the production of ion-pairs throughout the protoplasmic system, albeit to a very low degree. It is, however, very difficult to imagine adequate sensitivity of the living system to enable it to differentiate the direction of the minute gradients in ion-pair formation, or in physical excitation, which would be a consequence of the reduction in intensity with increasing distance from the source. As is evident from Figure 1, the width of the planarian body (about 1 mm.), at a distance of about 18 cm. from the source, would permit only an extremely small intensity difference across the body. However, if this is truly the mechanism of directional resolution of the gamma source, the capacity of the organism to distinguish minute differences in intensity of gamma radiation becomes underscored.

This responsiveness to very weak gamma radiation displays some of the same types of characteristics which have been described previously for responses to very weak electrostatic and magnetostatic fields. For all three kinds of fields the character of the response has been shown to possess a "compass-direction effect" for organisms as different as snails and planarians. The response to gamma radiation, as with response to extremely weak electrostatic fields, appears to be maximum when the organism is oriented, during daylight hours, in a N–S axis and minimum when it is directed in an E–W one. The response to gamma, however, is in the same direction for both N and S orientations, while for electrostatic fields, the two responses are of opposite sign.

In common with response of planarians to very weak magnetic fields, the sign of the response to the gamma radiation is in natural conditions the same for both N and S orientations. Another similarity with magnetic response is evident. The response to gamma radiation in snails (Brown, Webb and Johnson, 1962) appears to exhibit a monthly variation. This suggests that the gamma responses are related to the biological-clock phenomenon. This study supports a conclusion that response of the worms to gamma radiation also displays solar-day, lunar-day, and perhaps annual variations. It is interesting to speculate that response to gamma radiation may contribute to the annual rhythm in compass-directional behavior in planarians reported earlier (Brown, 1962a) and now confirmed during this study.

The compass-directional differences in response of *Dugesia* to gamma radiation are very pronounced. The conspicuous responsiveness to the gamma radiation when the experimental gamma change involves an E–W axis, and the essential absence of response when the gamma axis is a N–S one supports the suggestion that the perception of changes in gamma pattern may be related to biological-clock and compass phenomena. The major periods of the biological clocks are related to rotation and revolution of the earth relative to sun or moon. The earth's rotation relative to sun and moon, is, of course, principally an E–W, and not a N–S, one. Therefore, it is plausible to speculate that this particular compass-directional sensitivity is a biological adaptation contributing to the recognition of the major geophysical cycles by this subtle means. This possibility is being explored.

Summary

1. The common planarian worm, *Dugesia dorotocephala,* displays a significant orientational response to increase in Cs^{137} gamma radiation when the increase is no greater than 6 times background.

2. The worms are able to distinguish the direction of the weak gamma source, turning away from it, whether it is presented on the right or left side. The response sign is, therefore, the same as that of the response of these negatively phototactic worms to visible light.

3. There is a clear compass-directional relationship of the responsiveness to the experimental gamma radiation. A conspicuous negative response is present when the worms are traveling northward or southward in the earth's field with the gamma change in an east-west axis. No statistically significant mean turning response to the gamma radiation is found when the worms are traveling eastward or westward in the earth's field with the gamma change in a north-south axis.

4. The previously observed annual fluctuation in the character of the monthly orientational rhythm of north-directed worms has been confirmed in an additional year of study. During colder months, the rhythm is monthly; during warmer months it is semi-monthly.

5. There is a semi-monthly fluctuation in the response of *Dugesia* to weak gamma radiation during mid-morning hours, the worms turning away from the source for four days prior to new and full moon, and toward it for two days following new and full moon. The stronger the field strength, up to 9 times background, the larger the amplitude of the rhythm.

6. There is a direct relationship between intensities of gamma radiation between that of background and 9 times background, and the strength of the negative response of the worms.

7. Evidence suggests that the negative response of *Dugesia* to a gamma source may be modified by experimental alteration of the natural ambient electrostatic field.

8. Some possible biological significances of this remarkable responsiveness to gamma radiation, and its particular properties, are discussed briefly.

LITERATURE CITED

Brown, F. A., Jr., 1962a. Responses of the planarian, *Dugesia,* and the protozoan, *Paramecium,* to very weak horizontal magnetic fields. *Biol. Bull.,* 123: 264–281.

Brown, F. A., Jr., 1962b. Response of the planarian, *Dugesia,* to very weak horizontal electrostatic fields. *Biol. Bull.,* 123: 282–294.

Brown, F. A., Jr., M. F. Bennett and H. M. Webb, 1960. Magnetic compass response of an organism. *Biol. Bull.,* **119**: 65–74.

Brown, F. A., Jr., W. J. Brett, M. F. Bennett and F. H. Barnwell, 1960. Magnetic response of an organism and its solar relationships. *Biol. Bull.,* **118**: 367–381.

Brown, F. A., Jr., H. M. Webb and F. H. Barnwell, 1962. A relationship between "compass-direction" response of snails and response to very weak right-angle electrostatic gradients. *Amer. Zool.,* **2**: 509.

Brown, F. A., Jr., H. M. Webb and W. J. Brett, 1960. Magnetic response of an organism and its lunar relationships. *Biol. Bull.,* **118**: 382–392.

Brown, F. A., Jr., H. M. Webb and L. G. Johnson, 1962. Orientational responses in organisms effected by very small alterations in gamma (Cs^{137}) radiation. *Biol. Bull.,* **123**: 488–489.

Palmer, John D., 1962. The effect of weak magnetic fields on the spatial orientation and locomotory responses of *Volvox aureus.* Doctoral Dissertation, Northwestern University, June, 1962.

Palmer, John D., 1963. Organismic spatial orientation in very weak magnetic fields. *Nature,* **198**: 1061–1062.

Webb, H. M., F. A. Brown, Jr. and W. J. Brett, 1959. Effects of imposed electrostatic fields on the rate of locomotion in *Ilyanassa. Biol. Bull.,* **117**: 430–431.

Webb, H. M., F. A. Brown, Jr. and T. E. Schroeder, 1961. Organismic responses to differences in weak horizontal electrostatic fields. *Biol. Bull.,* **121**: 413.